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What Will the Future Bring for Biological Invasions on Islands? An Expert-Based Assessment

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Edited by:

Ross Taylor Shackleton,
University of Lausanne, Switzerland

Reviewed by:

Louisa Wood,
Centre for Environment, Fisheries
and Aquaculture Science (CEFAS),
United Kingdom
Ana Sofia Vaz,
University of Granada, Spain

*Correspondence:

Bernd Lenzner
bernd.lenzner@univie.ac.at

†ORCID ID:

Bernd Lenzner
orcid.org/0000-0002-2616-3479
Céline Bellard
orcid.org/0000-0003-2012-1160
Franck Courchamp
orcid.org/0000-0001-7605-4548
Christophe Diagne
orcid.org/0000-0002-6406-1270
Marina Golivets
orcid.org/0000-0003-1278-2663
Severin D. H. Irl
orcid.org/0000-0002-1734-8607
Ingolf Kühn
orcid.org/0000-0003-1691-8249
Brian Leung
orcid.org/0000-0002-8323-9628
Chunlong Liu
orcid.org/0000-0002-3376-4555
Núria Roura-Pascual
orcid.org/0000-0003-0025-2972
Hanno Seebens
orcid.org/0000-0001-8993-6419

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**Bernd Lenzner^{1*†}, Guillaume Latombe¹, César Capinha², Céline Bellard^{3†},
Franck Courchamp^{3†}, Christophe Diagne^{3†}, Stefan Dullinger¹, Marina Golivets^{4†},
Severin D. H. Irl^{5†}, Ingolf Kühn^{4,6,7†}, Brian Leung^{8†}, Chunlong Liu^{9†}, Dietmar Moser¹,
Núria Roura-Pascual^{9†}, Hanno Seebens^{10†}, Anna Turbelin³, Patrick Weigelt¹¹ and
Franz Essl¹**

¹ Department of Botany and Biodiversity, University of Vienna, Vienna, Austria, ² Centro de Estudos Geográficos, Instituto de Geografia e Ordenamento do Território, Universidade de Lisboa, Lisbon, Portugal, ³ Université Paris-Saclay, CNRS, AgroParisTech, Ecologie Systématique Evolution, Orsay, France, ⁴ Department of Community Ecology, Helmholtz Centre for Environmental Research – UFZ, Halle, Germany, ⁵ Biogeography and Biodiversity Lab, Institute of Physical Geography, Goethe-University Frankfurt, Frankfurt, Germany, ⁶ Department of Geobotany and Botanical Garden, Martin Luther University Halle-Wittenberg, Halle, Germany, ⁷ German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany, ⁸ Department of Biology, McGill University, Montreal, QC, Canada, ⁹ Departament de Ciències Ambientals, Facultat de Ciències, Universitat de Girona, Girona, Spain, ¹⁰ Senckenberg Biodiversity and Climate Research Centre (SBK-F), Frankfurt, Germany, ¹¹ Biodiversity, Macroecology and Biogeography, University of Göttingen, Göttingen, Germany

Biological invasions are a major threat to global biodiversity with particularly strong implications for island biodiversity. Much research has been dedicated towards understanding historic and current changes in alien species distribution and impacts on islands and potential changes under future climate change. However, projections of how alien species richness and impacts on islands might develop in the future are still lacking. In the absence of reliable projections, expert-based assessments are a valuable tool to investigate the importance of different drivers and pathways and the distributions of potential impacts of future biological invasions. These insights can guide subsequent quantification efforts and inform invasive species management and policy. In this study, we performed a survey among 126 experts in invasion science ranging from scientists to managers and decision makers with a focus on island systems until the mid-21st century. The survey revealed that out of 15 drivers, six were considered important by almost all respondents (>90%). Of these, trade and transport was identified as most important at the introduction stage (99.2%) and land use/cover change as most important at the establishment (96.8%) and spread (95.2%) stage. Additionally, the experts considered that alien species were more likely to be introduced (93.7%) and spread (78.6%) as stowaways than through any other pathway. In general, respondents agreed that the impacts of alien species will increase on all types of islands, particularly on oceanic islands, followed by atolls and continental islands. Within islands, terrestrial ecosystems were assumed to be impacted more severely than marine ecosystems. Finally, the survey hints toward the potential for effective communication,

scientific research and increased pro-active management of alien species on islands to reduce their future consequences. Given the major threat represented by invasive alien species on islands, these results provide crucial insights relevant for global and regional conservation efforts.

Keywords: biodiversity change, biological invasions, drivers, islands, expert-based approach, plausible futures, scenarios, survey

INTRODUCTION

Biological invasions have been identified as one of the major threats to biodiversity worldwide and are an important facet of global environmental change (Maxwell et al., 2016; IPBES, 2018). Islands are hotspots of both endemic (Myers et al., 2000; Kier et al., 2009) and alien species richness (Bellard et al., 2017; Dawson et al., 2017; Essl et al., 2019a) with a subset of alien species – invasive alien species (IAS) – causing negative impacts on biodiversity and driving many recent extinctions (Tershy et al., 2015; Bellard et al., 2016). Current knowledge of the mechanisms driving biological invasions on islands, and of the threats IAS pose on island biota, largely relies on information from several well studied regions (e.g., Macaronesian Islands, Hawaii; e.g., Levine and D'Antonio, 1999; Daehler, 2006; Kueffer et al., 2014), while research in many other island regions is often less extensive or even lacking.

Two issues are crucial in understanding island invasions for conservation and scientific purposes: (i) a comparison of trends in alien species richness in mainland and island regions (Seebens et al., 2018); (ii) how environmental and socio-economic factors could change in relative importance over time for driving future invasions. Improved understanding of these issues should lead ultimately to better knowledge on how invasion impacts could change over time in magnitude and geographical distribution (Lenzner et al., 2019). Answers to these questions are complex, as drivers of biological invasions may change distinctly across taxa, habitats and island regions (Latombe et al., 2019b).

Assessments of potential future invasions and impacts of alien species require the use of scenarios of future trajectories for various facets of specific systems, such as invasion pathways or other drivers of alien species richness, composition, abundance and impact. For most other key drivers of biodiversity change such scenarios have already been established. These include climate change (Moss et al., 2010; IPCC, 2014), land-use change (Hurt et al., 2009), sea-level rise (Wetzel et al., 2012; Hinkel et al., 2014) and human population change (Lutz et al., 2014). However, comprehensive long-term scenarios are still missing for biological invasions (Lenzner et al., 2019). One reason for the lack of scenarios for potential future states of biological invasions is their complex nature and until recently a lack of comprehensive global datasets (Courchamp et al., 2017). Moreover, biological invasions have arisen from a complex interplay of environmental, socio-economic and societal changes that are difficult to project using classical modeling techniques, like static habitat suitability models, population dynamic models or cellular automata (see Buchadas et al., 2017; Capinha et al., 2018; Lenzner et al., 2019). To overcome such multi-disciplinary

challenges, combining classical forecasting techniques with expert-based assessments has proven to be a promising approach (e.g., through qualitative surveys; Berg et al., 2016; Symstad et al., 2017; Reside et al., 2018).

Here, we present the outcome of an expert survey with the aim to identify the importance of different drivers and pathways of biological invasions on islands in the 21st century. Further, based on the knowledge of experts on island ecology and conservation, we aim to gain a better understanding of potential future impacts of biological invasions on islands. The identification of these aspects of biological invasions in the future is crucial for subsequent quantification efforts. Specifically, we focus on three overarching questions: (1) Which drivers will contribute most strongly to alien species richness increase during the introduction, establishment and spread phases of the invasion process? (2) Which pathways will substantially increase alien species richness during the introduction and spread phases of the invasion process? (3) How strongly will different island contexts be affected by an increase in alien species richness?

MATERIALS AND METHODS

Driver Selection

A set of 15 major drivers of biological invasions was selected during a workshop on scenarios for biological invasions held in Vienna, Austria in October 2016. A comprehensive list of drivers of biological invasions based on an extensive literature search was compiled prior to the workshop. This list was then provided to a group of invasion scientists with complementary backgrounds in related fields (e.g., land-use change, systems analysis, global environmental change), who assessed the importance of each driver and identified a set of 15 most relevant ones for future biological invasions. For the selection procedure, each workshop participant identified three most important drivers for future invasions and the highest ranked drivers were selected. This set of drivers underlies complementary assessments of biological invasion scenarios that are currently under development (Essl et al., 2019b, 2020; Roura-Pascual et al., under review). We adopted this updated list of 15 drivers and classified them into three thematic groups: (i) environmental change drivers (climate change; ocean acidification; eutrophication and pollution; biodiversity loss and degradation), (ii) socio-economic activity drivers (trade and transport; land use/cover change; socio-economic change; demography and migration) and (iii) society and technology (awareness, values and lifestyle; recreation and tourism; communication and outreach; technology and innovation; cooperation, legislation and agreements; IAS science;

IAS management). For the description of individual drivers and their rationale as provided in the questionnaire, see **Table 1**.

Survey Design

The questionnaire was divided into four sections: (1) drivers of biological invasions, (2) pathways of biological invasions, (3) effects of alien species richness increases related to three island contexts (i.e., types, systems and habitats), and (4) personal background and expertise of respondents. Section 1 contained questions related to three thematic groups of drivers (see above). For each thematic group, we asked the survey respondents to indicate which of the drivers will strongly increase alien species richness on islands within the 21st century in each of the three main stages of invasion (i.e., introduction, establishment

and spread). In section 2, we asked which pathways will substantially increase alien species richness in the introduction and spread stages on islands within the 21st century. The pathways are based on Hulme et al. (2008) and include six categories: stowaway, escape, contaminant, release, corridor, unaided. Section 3 related to the respondents' projection of how strongly an increase in invasive alien species richness in the 21st century will affect different island types (oceanic islands, continental islands and atolls), island systems (marine, freshwater, terrestrial) and habitats (e.g., wetlands, agricultural land; see the full list in **Supplementary Material S2**). Finally, section 4 aimed at collecting background information on the level and area of expertise of the respondents (focal taxonomic groups, geographic regions, island types, and socio-economic status of

TABLE 1 | Overview table of the 15 drivers used in the survey and their rationale on how they might affect biological invasions.

Driver	Rationale
Environmental Change	
Climate Change	Climate change is likely to change mean temperatures, change precipitation patterns etc. and increase the frequency, magnitude and distribution of extreme events, causing disturbances that may create opportunities for alien species. These changes are likely to interact synergistically with biological invasions, although substantial variation exists among taxa and geographic regions.
Ocean Acidification	Increasing CO ₂ -levels will increase ocean acidification, thereby affecting water chemistry and native biota
Eutrophication and Pollution	Anthropogenic input of pollutants and nutrients via fertilization, run off and atmospheric deposition affect many ecosystems, often promoting opportunistic species.
Biodiversity Loss and Degradation	Downgrading and loss of (near-) natural ecosystems, loss of species and functional groups, and positive feedbacks (facilitation, invasional meltdown) may have distinct implications on species compositions.
Socio-Economic Activity	
Trade and Transport	Key features of trade and transport such as the type of goods that are transported, the volumes that are traded, the means and velocity of transport, and the routes of transport are likely to change in the future. Emerging modes of trading (e.g., via internet) that are more difficult to regulate may become more relevant for biological invasions. Trade includes also specific high-risk pathways such as pet and horticultural trade, wood products, ballast water and biofouling, and the emergence of new trade routes that are becoming accessible due to climate change (Arctic shipping routes) or economic interests (Suez Canal and Panama Canal extension, Nicaragua Canal).
Land Use/Cover Change	Demand for food supplies, clothing, housing, etc. and for new materials (e.g., for bioenergy production) will likely increase in the 21st century. The resulting changes in land-use (incl. the intentional use of IAS) and land-use intensity may cause losses of ecosystems, degradation of used ecosystems, increase fragmentation and disturbance of ecosystems, and alter resource dynamics.
Socio-Economic Change	The level of socio-economic activities (as measured by per capita GDP or similar metrics) is correlated with a wide range of changes of the environment (e.g., resource and energy uses, human mobility, land use) that may be relevant for determining the success of biological invasions.
Demography and Migration	Changes in the size and distribution of human populations and migration of humans may influence biological invasions via a range of correlated relevant impacts.
Society and Technology	
Awareness, Values and Lifestyle	The awareness and values of the citizens, stakeholders, business, NGOs and politicians toward biological invasions is important for establishing and implementing invasive alien species (IAS) policies and management. Includes also the views of people who are opposing actions on IAS on ethical grounds (e.g., animal-right movements) or because they consider it unwarranted.
Recreation and Tourism	(Outdoor) recreation (incl. gardening, hunting, fishing, hiking) and tourism may impact on biological invasions in a range of different ways.
Communication and Outreach	The way, tone and intensity of communication on biological invasions with(in) the wider public and decision makers may influence the public perception of and action on invasive alien species (IAS).
Technology and Innovation	The general level of innovation and the extent to which new technologies are introduced, accepted and become widely applied may have substantial implications for biological invasions (e.g., biocontrol safety).
Cooperation, Legislation and Agreements	The level of political and institutional cooperation (within and between nations) and the ensuing legislation and agreements on biosecurity and biological invasions, their relationship with other relevant topics (e.g., trade agreements), and the level of implementing these policies.
IAS Science	Scientific research on invasive alien species (IAS) may improve the understanding of the invasion process of IAS, improve management techniques, increase data availability on alien species etc. Further, research priorities may be more or less relevant for IAS management and policy.
IAS Management	The comprehensiveness and level of implementation of invasive alien species (IAS) management, and the available resources and institutional capacities may be important for the level of biological invasions.

Within the questionnaire, the drivers were grouped in three subcategories: (i) environmental change, (ii) socio-economic activity, and (iii) society and technology.

their study area) and personal information (gender, age, country of home institution).

The questionnaire was implemented using Google Forms®. The respondents had to answer all questions (i.e., they were not able to skip a questions) in the provided order and could only switch to the next page once all questions had been answered. Introductory text and guidance were provided for each question where necessary (see survey layout in **Supplementary Material S2**). Survey responses were in the form of a Likert scale (e.g., strongly disagree < disagree < neutral < agree < strongly agree, or low < medium < strong). The link to the online survey was distributed among the 262 participants of the 3rd International Conference of Island Biology 2019 on La Réunion Island.¹ The survey was sent out twice during the conference and once after the conference (July 2019). Additionally, to reach an even wider audience, the survey was circulated once through relevant mailing lists (August 2019), namely the Island Conservation Network mailing list (Island-L; islands-l@listserv.bgc.org) which has 382 subscribers (as of February 2020) and the ALIENS-L mailing list (aliens-l@list.auckland.ac.nz) of the Invasive Species Specialist Group (ISSG) of the IUCN Species Survival Commission with 1449 subscribers (as of February 2020).

Data Preparation and Statistical Analysis

For two of the questions concerning their personal background and study system, the respondents were given the option to provide free text additions to their answers. Where possible, we integrated the additional information on personal background into the default categories, whereas the answers stating a role in policy or government-related positions were assigned to a new additional category named “policy.” For the question on study systems, we likewise added an additional post-survey category named “island-like system”; this category encompassed respondents who stated they work with island-like systems (e.g., fragmented landscapes) but not “true” islands. We provide the original data and their category assignment in the **Supplementary Table S1**.

To assess the agreement between respondents on the importance of the different drivers, pathways and island characteristics for each stage of invasion, we fitted proportional odds models with a logit-link function using the ‘*clm*’-function in the package ‘ordinal’ (Christensen, 2019) in the statistical programming software R version 3.6.1 (R Core Team, 2019). Individual models were run for each invasion stage for section 1 (three models: introduction, establishment and spread) and 2 (two models: introduction and spread) of the survey. Survey responses were modeled as a function of the individual categorical drivers of invasion. Similarly, three different models were run for section 3 to assess how island types, systems and habitats might be affected in the future. Again, survey responses were modeled as a function of the individual categorical drivers of invasion. Model fit was assessed visually and none of the models violated the proportional odds assumption.

To assess the agreement or disagreement of respondents with the postulated contribution of drivers to future invasions, we evaluated whether given answers differed statistically from a neutral assumption of random answers. To this end, we introduced an additional factor level (i.e., formally a new driver) which was assumed to be assessed at random by all respondents, i.e., we assigned an equal number ($n = 25$) of responses to the response options “strongly disagree,” “disagree,” “agree” and “strongly agree” and 26 responses to the neutral response option to resemble the 126 respondents of the survey. We then used this dummy category as a reference level and all the other drivers were tested on whether they differed significantly from it. A significantly higher odds ratio was interpreted as agreement with the postulated effect, a non-significantly different one as neutral and a significantly lower odds ratio as disagreement.

RESULTS

Personal Background and Expertise

In total, 126 responses were obtained. If fully attributed to either of the channels through which we distributed the survey, this would equate to response rates of 48% of the conference participants, 32% of the members of the Island-L mailing list, or 9% of the Aliens-L mailing list. The gender ratio among the respondents was 74 men to 50 women with two respondents not providing this information (option “prefer not to say”). The age ranged from <25 ($n = 3$) to >65 ($n = 10$) years of age with most people in the age class of “36–45” ($n = 51$). The responses regarding the location of home institution (which was an open-text question) sometimes included only a country or an island group, which might have somewhat distorted the true picture as many islands are administrative units of certain countries; meanwhile, four participants did not provide a clear answer that could be assigned to a country or island group. Overall, home institutions were distributed across the world with participants situated on islands within all major ocean realms, as well as on all continents, but most participants had their home institutions in Europe ($n = 42$) followed by mainland United States ($n = 28$). However, most researchers worked on North Pacific Islands ($n = 37$), North Atlantic Islands ($n = 37$), Indian Ocean Islands ($n = 33$) and islands in the South Pacific Ocean ($n = 26$). Fewest worked on South Pacific Islands ($n = 14$), Southern Ocean Islands ($n = 6$), and Arctic Ocean Islands ($n = 1$). Finally, 19 respondents indicated that they worked at a global scale. Within their study regions, respondents mainly worked with oceanic islands ($n = 108$), followed by continental islands ($n = 39$) and atolls ($n = 16$). Most islands studied by the respondents are situated in developed countries ($n = 85$), followed by developing ($n = 40$) and emerging ($n = 39$) ones (see the questionnaire in **Supplementary Material S2** for definitions of the socio-economic background of the study regions). Most respondents indicated that their professional background was in conservation management ($n = 80$), followed by applied research ($n = 55$), basic research ($n = 52$), policy ($n = 21$), other stakeholders ($n = 4$) and interested citizens ($n = 3$). Finally, respondents working in the marine realm had highest expertise with vertebrates,

¹<https://ib2019.sciencesconf.org/>

followed by invertebrates, plants and microorganisms. In the terrestrial realm, highest expertise was indicated for plants, followed by vertebrates, invertebrates and microorganisms. All data on personal information and scientific background and expertise are summarized in **Supplementary Figure S1**.

Drivers of Increase in Alien Species Richness

For the introduction stage, respondents almost uniformly pinpointed trade and transport (99.2% agreement) as an important driver of future alien species richness, followed by recreation and tourism (92.9% agreement) and demography and migration (92.8% agreement), and with some respondents indicating distance by land use/cover change (80.2% agreement), socio-economy (76.2% agreement) climate change (68.3% agreement) and biodiversity loss and degradation (68.2% agreement). The remaining drivers were not considered to contribute to the increase in alien species richness at the introduction stage, i.e., the agreement for these drivers was <50% and the odds ratio of agreement to their contribution was not significantly higher as for the dummy category (see **Figures 1, 2A** and **Table 2A**).

At the establishment stage, the main drivers of the increase in alien species richness were considered to be land use/cover change (96.8% agreement), biodiversity loss and degradation (96.0% agreement), climate change (93.7% agreement), and demography and migration (85.7% agreement) as well as socio-economy (80.2% agreement), recreation and tourism (74.6% agreement), eutrophication and pollution (73.8% agreement) and trade and transport (65.9% agreement). The remaining drivers were considered to not contribute substantially to alien species richness increase at the establishment stage, with <50% agreement and odd ratios that did not deviate significantly from the dummy category (see **Figures 1, 2B** and **Table 2B**).

At the spread stage, the drivers of alien species richness were considered to be land use/cover change (95.2% agreement), climate change (91.3% agreement), biodiversity loss and degradation (91.3% agreement), demography and migration (88.9% agreement), recreation and tourism (86.5% agreement), trade and transport (86.5% agreement), socio-economy (81.0% agreement) and eutrophication and pollution (68.2% agreement). The remaining drivers were considered not to contribute substantially to alien species richness increase at the spread stage, with <50% agreement and non-significantly deviating odd ratios from the dummy category (see **Figures 1, 2C** and **Table 2C**).

Across invasion stages, two drivers – technology and innovation and awareness, values and lifestyle – consistently showed no clear trend, i.e., not deviating significantly from the dummy category. For technology & innovation respondents disagreed slightly more with their importance as a driver of alien species richness (introduction: 30.2% agreement and 38.9% disagreement; establishment: 28.6% agreement and 41.3% disagreement; spread: 27.0% agreement and 41.3% disagreement; see **Figure 2** and **Table 2**), whereas for awareness, values and lifestyle, the results were more balanced (introduction: 38.9% agreement and 35.7% disagreement; establishment: 35.7%

agreement and 33.3% disagreement; spread: 34.9% agreement and 32.5% disagreement; see **Figure 2** and **Table 2**).

Pathway Contribution to Increased Alien Species Richness

For the introduction stage, respondents consistently agreed that all six pathways will substantially contribute to an increase in alien species richness, i.e., > 50% agreement and significantly higher odd ratios than for the dummy category for all of them. The responses identified strongest agreement for species introductions as stowaway (93.7% agreement), followed by escapes (89.7% agreement), contaminants (86.5% agreement), release (74.6% agreement), corridor (67.5% agreement) and unaided (65.9% agreement).

For the spread stage, respondents agreed again to all introduction pathways increasing alien species richness. Strongest agreement was provided for stowaway (78.6% agreement), escape (74.6% agreement) and corridor (71.4% agreement), followed by contaminant (69.8% agreement), unaided (65.9% agreement) and release (64.3% agreement). The overall agreement on pathway contributions to alien species richness was stronger at the introduction rather than the spread stage. See **Figure 3** and **Table 3** for the answer structure and model outputs.

Effects of Increase in Alien Species Richness Increase

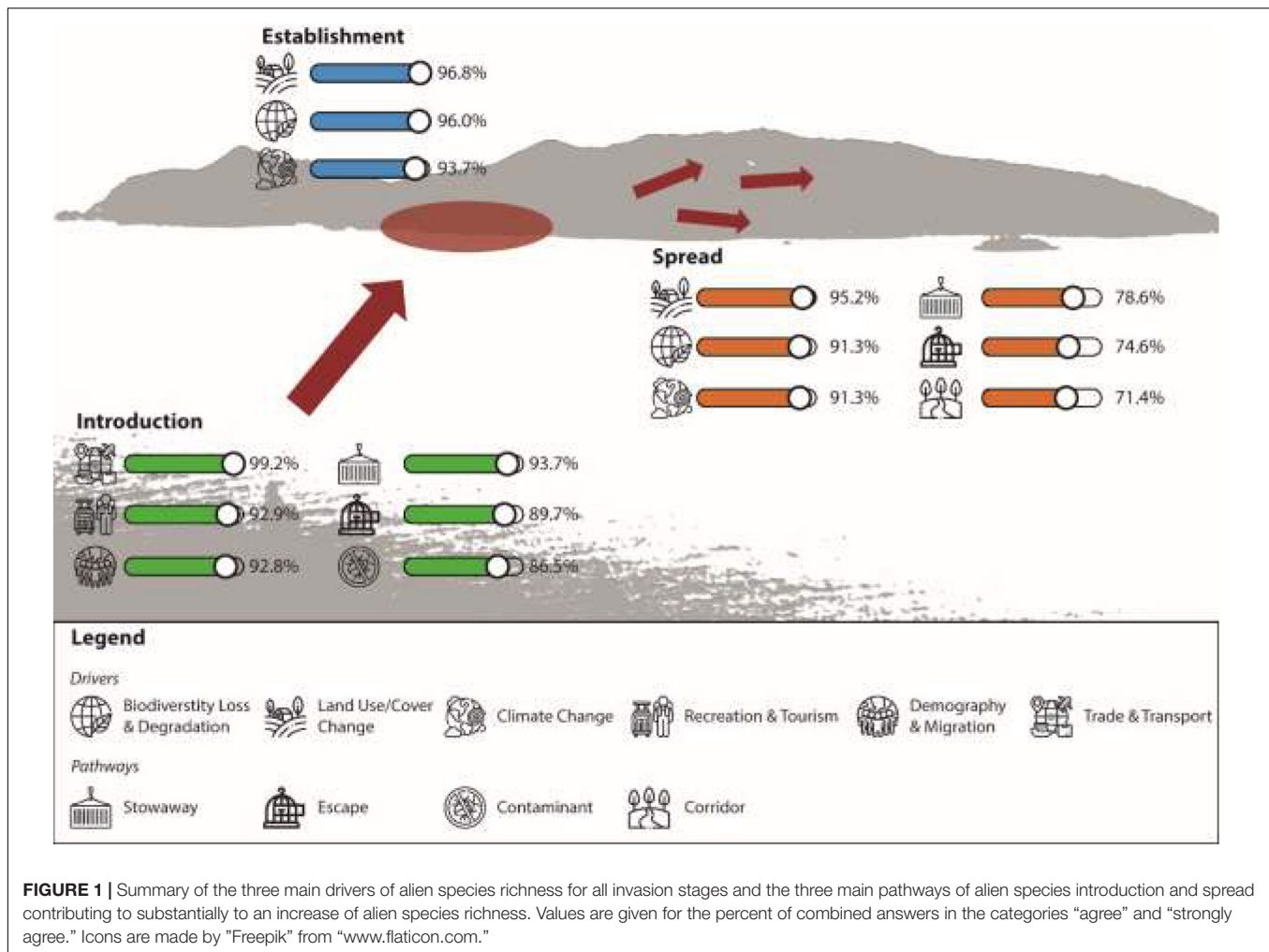
All respondents agreed that each island type would be affected by a future increase in alien species richness, with oceanic islands being affected more strongly (85.7% strong effects) than atolls (57.1% strong effects) and continental islands (52.4% strong effects).

The respondents were also consistently convinced that an increase in invasive alien species richness will have ecological implications across different types of island systems. Strongest effects were expected for terrestrial (81.8% strong effects), freshwater (69.0% strong effects) and marine systems (65.9% strong effects).

Across habitats, strongest effects were suggested for terrestrial coastal habitats (70.6% strong effects), wetlands (67.5% strong effects), dry forests (60.3% strong effects), marine habitats (57.1% strong effects), and settlements (52.4% strong effects). Least strong effects were anticipated for mountain and alpine habitats (43.6% strong effects; odds ratio = 3.6; p -value = 0.004) and (semi-)deserts (25.4% strong effects; odds ratio = 0.8; p -value = 0.346). For information on the answer structure and model outputs for all impact related analyses see **Figure 4** and **Table 4**.

DISCUSSION

Our study identifies six drivers that, according to experts, should substantially contribute to alien species richness increase on islands during the 21st century. At the introduction stage these drivers are mainly related to socio-economic activities like trade and transport, recreation and tourism and demography and



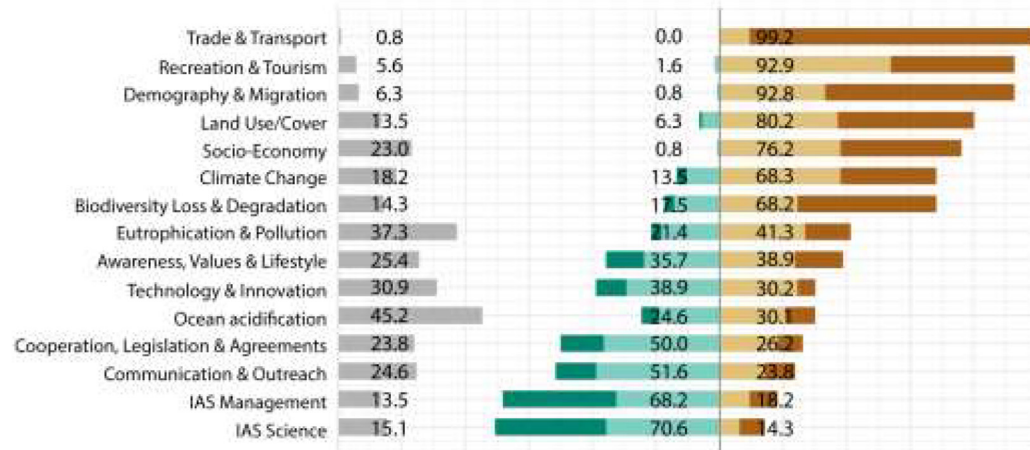
migrations. At the establishment and spread stage the drivers change and mainly include environmental and anthropogenic change drivers, namely land use/cover change, biodiversity loss and degradation and climate change (Figure 1). Major pathways assumed to substantially increase future alien species richness at the introduction stage are stowaways, escapes and contaminants. At the spread stage the first two pathways remain similar, with contaminants being third in importance (Figure 1). All results are discussed in more detail in the following sections.

Drivers and Pathways

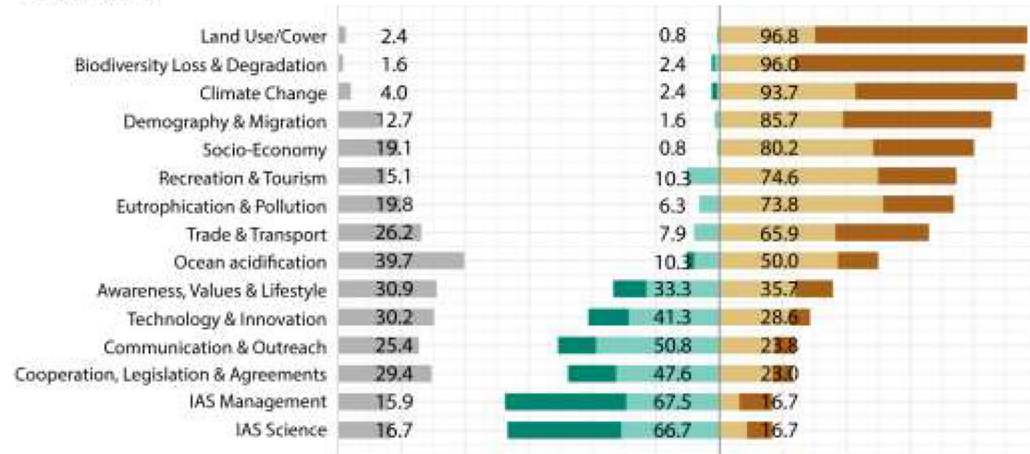
Per definition, alien species are distributed by human agency to regions outside their native range and hence their introduction is inherently tied to the movement of commodities and people around the world (Essl et al., 2018). Thus, respondents unanimously identified socio-economic activity drivers such as trade and transport, demography and migration and recreation and tourism as major drivers of future alien species richness on islands. As current scenarios of global trade assume that traded commodities will double or increase more than 4-fold between 2015 and 2050 (ITF, 2017), the numbers of species introductions are likely to increase for islands in the

future. Additionally, the global trade network is projected to change over the course of the 21st century, including a stronger integration of hitherto less well integrated regions, which would change the frequencies, volumes and travel times of traded goods (World Trade Organisation, 2013). With changing frequencies and volumes of traded goods, propagule pressure and colonization will increase, and shorter travel times will increase the survival probability of transported propagules, all contributing to higher alien species richness in respective regions (Seebens et al., 2015; Sardain et al., 2019). Furthermore, the respondents identified stowaways and contaminants as the leading pathways, which is in line with what has been observed in other studies (Hulme, 2009; Pergl et al., 2017). The outlined changes in global trade are not exclusive to islands but apply to all regions worldwide. However, islands typically have high volumes of imports as most commodities are not produced on the islands themselves, which together with higher invasibility compared to mainland regions increases their invasion risk (Hulme, 2009; Moser et al., 2018; OECD, 2018). Hence, on islands the proportion of unintentionally introduced alien species will likely increase. Given the isolated nature of islands, biosecurity measures are more easily implemented compared to mainland

A Introduction



B Establishment



C Spread

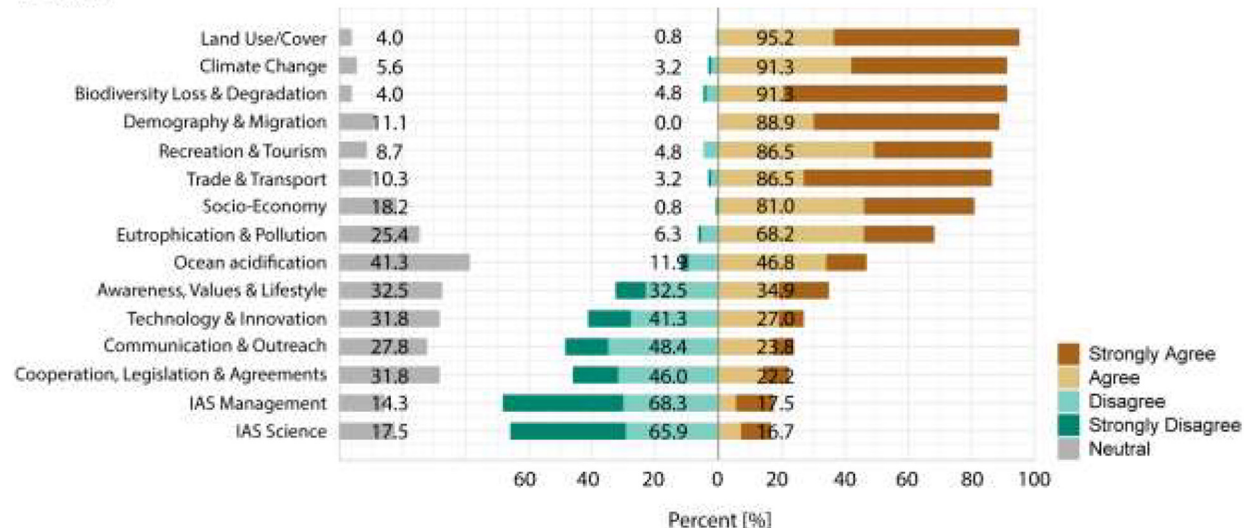


FIGURE 2 | Summary of the answers provided by the 126 respondents for the first section of the survey. Respondents were asked which of the drivers will significantly increase alien species (A) introductions, (B) establishment and (C) spread to/on islands in the 21st century. Answers were provided on a 5-point Likert scale with the categories: strongly disagree, disagree, neutral, agree and strongly agree. Shown is the percentage of agreement with each of the categories. Values are given for the percent of answers in the neutral category and for the disagreement and agreement categories grouping the respective two answer possibilities.

TABLE 2 | Proportional odds models analyzing if the 15 drivers of biological invasions addressed in the survey significantly increase alien species (A) introduction, (B) establishment, and (C) spread on islands in the 21st century.

(A)	Introduction		
	Odds Ratio	CI	p
Predictors			
Awareness, Values and Lifestyle	1.1	0.69–1.76	0.68
Climate Change	3.75	2.34–5.99	<0.001
Biodiversity Loss and degradation	5.03	3.09–8.18	<0.001
Communication and outreach	0.6	0.37–0.95	0.03
Cooperation, legislation and agreements	0.62	0.39–0.99	0.04
Demography and migration	13.61	8.31–22.27	<0.001
Eutrophication and Pollution	1.55	0.98–2.45	0.06
IAS management	0.25	0.15–0.40	<0.001
IAS science	0.23	0.14–0.37	<0.001
Land Use/Cover change	6.69	4.16–10.77	<0.001
Ocean Acidification	1.14	0.72–1.79	0.58
Recreation and tourism	7.55	4.74–12.03	<0.001
Socio-Economic change	5.8	3.63–9.26	<0.001
Technology and Innovation	0.83	0.53–1.32	0.43
Trade and transport	74.48	37.85–146.58	<0.001
Threshold coefficients:			
Strongly disagree Disagree	0.12	0.08–0.17	<0.001
Disagree Neutral	0.55	0.39–0.78	0.001
Neutral Agree	1.84	1.30–2.61	0.001
Agree Strongly agree	8.41	5.86–12.07	<0.001

(B)	Establishment		
	Odds Ratio	CI	p
Predictors			
Awareness, values and lifestyle	1.05	0.65–1.68	0.84
Climate change	13.01	7.96–21.25	<0.001
Biodiversity loss and degradation	29.69	17.40–50.67	<0.001
Communication and outreach	0.58	0.36–0.92	0.02
Cooperation, legislation and agreements	0.58	0.36–0.92	0.02
Demography and migration	10.24	6.28–16.69	<0.001
Eutrophication and pollution	4.25	2.66–6.80	<0.001
IAS management	0.23	0.14–0.38	<0.001
IAS science	0.25	0.15–0.40	<0.001
Land Use/Cover change	23.77	14.18–39.87	<0.001
Ocean acidification	2.11	1.33–3.35	0.002
Recreation and tourism	4.4	2.74–7.07	<0.001
Socio-Economic change	6.21	3.87–9.99	<0.001
Technology and innovation	0.73	0.46–1.17	0.19
Trade and transport	4.2	2.60–6.78	<0.001
Threshold coefficients:			
Strongly disagree Disagree	0.12	0.08–0.17	<0.001
Disagree Neutral	0.5	0.35–0.71	<0.001
Neutral Agree	1.82	1.27–2.59	0.001
Agree Strongly agree	11.17	7.69–16.22	<0.001

(Continued)

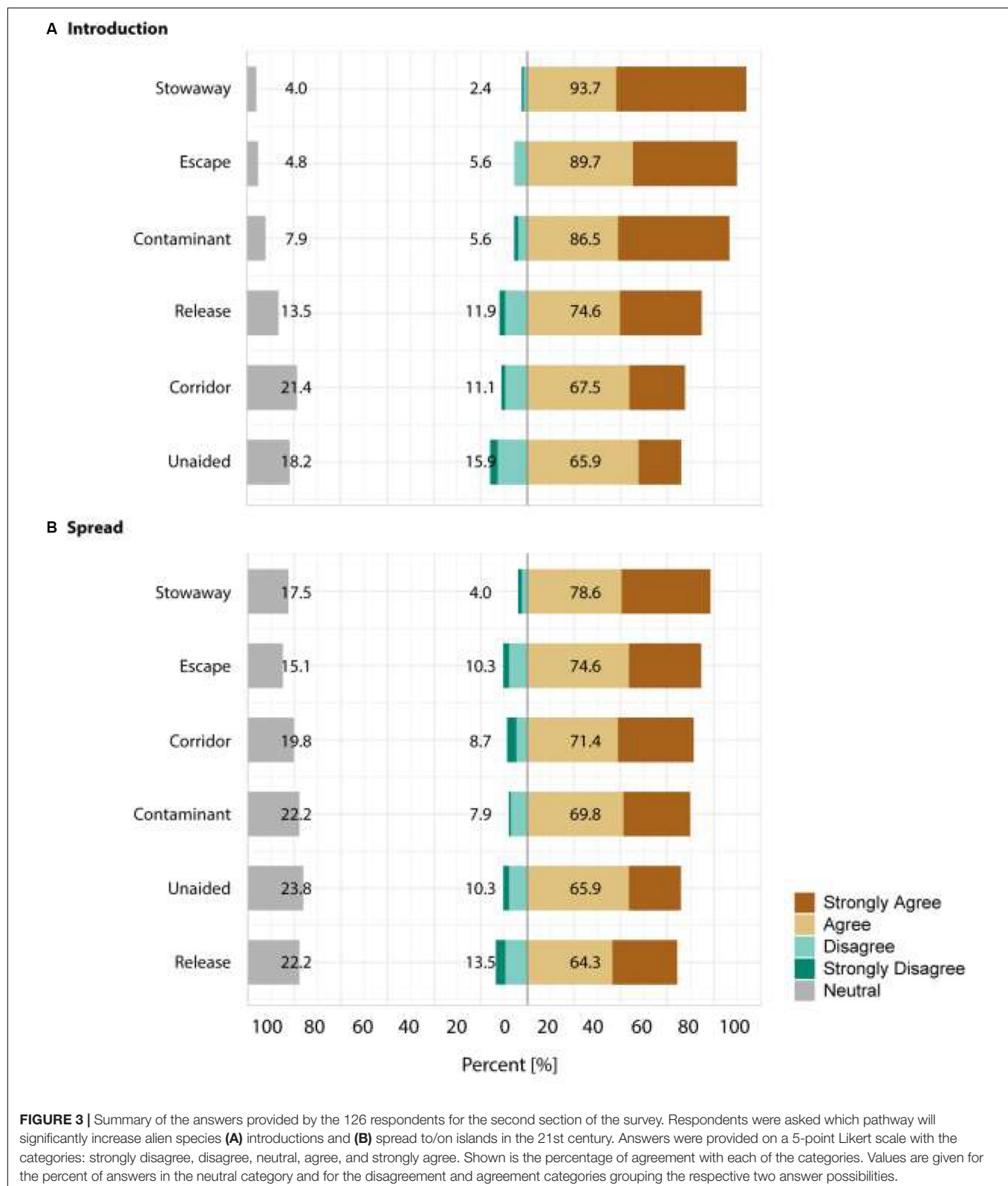
TABLE 2 | Continued

(C)	Spread		
	Odds Ratio	CI	p
Predictors			
Awareness, Values and Lifestyle	1.11	0.69–1.78	0.66
Climate Change	10.79	6.64–17.52	<0.001
Biodiversity Loss and Degradation	22.9	13.51–38.80	<0.001
Communication and Outreach	0.59	0.37–0.95	0.03
Cooperation, Legislation and Agreements	0.61	0.38–0.97	0.04
Demography and Migration	14.28	8.67–23.51	<0.001
Eutrophication and Pollution	3.65	2.29–5.81	<0.001
IAS Management	0.24	0.15–0.39	<0.001
IAS Science	0.25	0.16–0.41	<0.001
Land Use/Cover Change	15.54	9.46–25.54	<0.001
Ocean Acidification	1.93	1.22–3.05	0.01
Recreation and Tourism	7.2	4.48–11.56	<0.001
Socio-Economic Change	6.33	3.95–10.15	<0.001
Technology and Innovation	0.72	0.45–1.15	0.17
Trade and Transport	13.97	8.46–23.08	<0.001
Threshold coefficients:			
Strongly disagree Disagree	0.12	0.09–0.18	<0.001
Disagree Neutral	0.5	0.35–0.71	<0.001
Neutral Agree	1.86	1.31–2.65	0.001
Agree Strongly agree	9.78	6.77–14.14	<0.001

regions, and prevention measures are preferred and most cost-efficient in the context of islands (Leung et al., 2002; Russell et al., 2017).

The identified main drivers of future invasions differ between the introduction and the establishment stages. The drivers associated with the environment (e.g., climate change and biodiversity loss and degradation) and human activity (e.g., land use/cover change, socio-economy or demography and migration) become prevalent at the establishment stage. Anthropogenic habitat destruction has indeed been shown to strongly increase alien species richness and abundance across habitats, at the expense of native species richness (Sanchez-Ortiz et al., 2019). Other anthropogenic disturbances like infrastructure development additionally increase alien species establishment (Alexander et al., 2016; Haider et al., 2018), and urban and artificial environments already hold a high diversity of alien species, often buffering them from adverse environmental conditions (Strubbe and Matthysen, 2009). Finally, anthropogenic habitat transformation (IPBES, 2018), future climate change (Bellard et al., 2013; Harter et al., 2015), and socio-economic activity (Hulme, 2009; Seebens et al., 2015) also indirectly promote the establishment of new alien species through the loss of native biodiversity.

Overall, the participants assessed alien species spread to be promoted by a combination of drivers relevant at the introduction and establishment stages. The respondents particularly agree that land use/cover change, biodiversity loss and degradation and climate change will strongly contribute



to an increase of alien species richness in the future. These drivers are closely followed by the same drivers related to the movement of people (e.g., recreation and tourism) and

goods (e.g., trade and transport) that are most important at the introduction stage. This assumption appears intuitive, as with ongoing anthropogenic pressure and disturbance more suitable

TABLE 3 | Proportional odds models, analyzing which pathway will significantly increase alien species (A) introductions and (B) spread to/on islands in the 21st century.

	Introduction			Spread		
	Odds Ratio	CI	p	Odds Ratio	CI	p
Predictors						
Contaminant	9.15	5.59–14.97	<0.001	3.99	2.49–6.39	<0.001
Corridor	3.27	2.05–5.23	<0.001	4.43	2.75–7.13	<0.001
Escape	8.79	5.39–14.31	<0.001	4.49	2.80–7.22	<0.001
Release	4.9	3.03–7.95	<0.001	3.3	2.06–5.30	<0.001
Stowaway	13.34	8.08–22.01	<0.001	6.04	3.74–9.74	<0.001
Unaided	2.67	1.68–4.26	<0.001	3.15	1.98–5.02	<0.001
Threshold coefficients:						
Strongly disagree Disagree	0.15	0.10–0.23	<0.001	0.16	0.10–0.23	<0.001
Disagree Neutral	0.57	0.40–0.81	0.002	0.49	0.35–0.70	<0.001
Neutral Agree	1.49	1.05–2.12	0.026	1.74	1.22–2.48	0.002
Agree Strongly agree	9.93	6.78–14.54	<0.001	9.16	6.29–13.33	<0.001

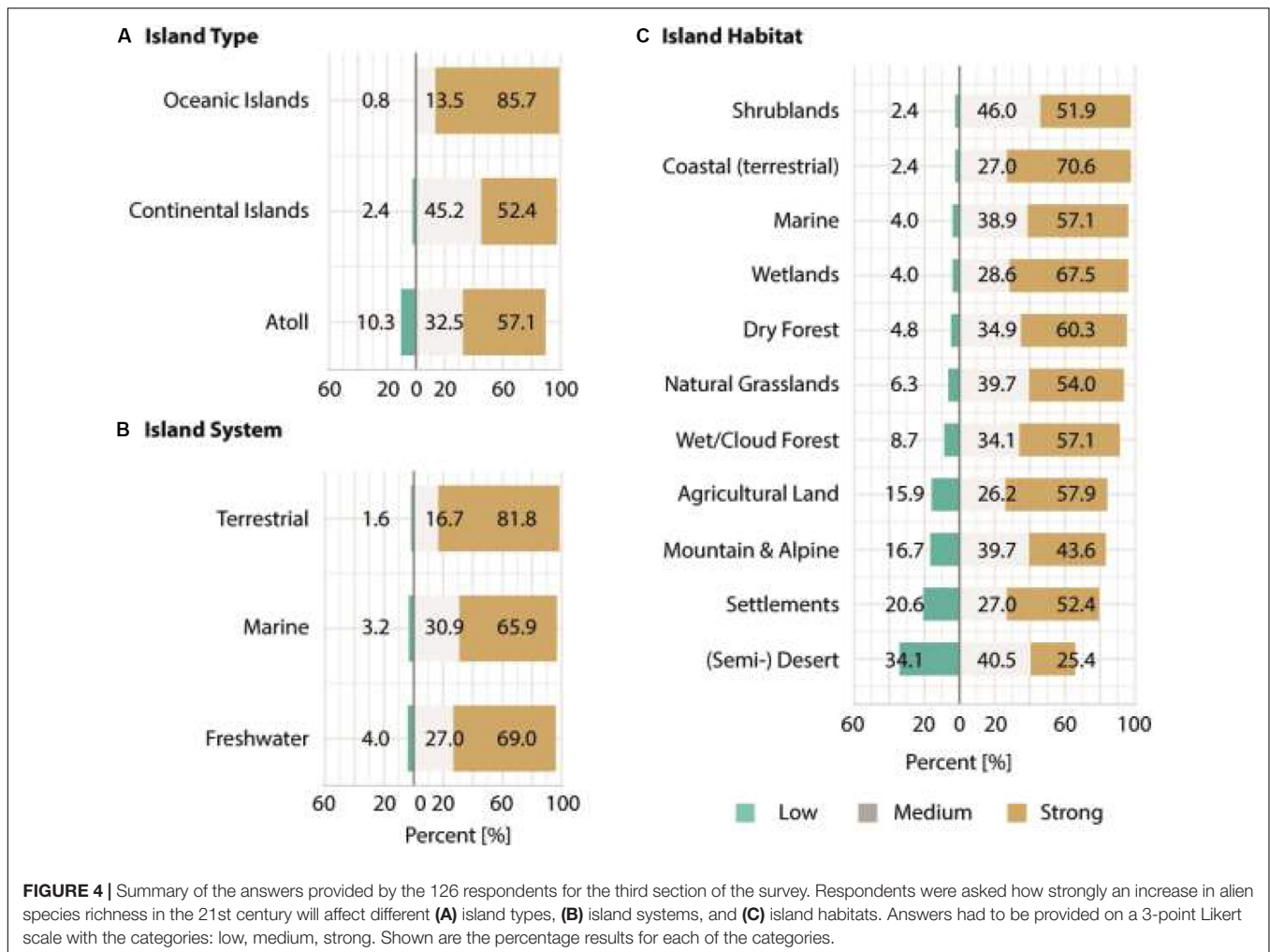
habitat for alien species opens up, and increased movement of people and goods then facilitates secondary spread of species within and between island groups. Similar to the introduction phase, unintentional dispersal pathways (i.e., stowaways and contaminants) appear to be most relevant for alien species richness increases at the spread stage.

The strong support for demography & migration across invasion stages as one of the main drivers for alien species on islands is indicative of complex dynamics with other drivers, especially tourism. This appears to contradict future projections of human population trends on islands, which indicate an earlier saturation or even a decrease of human population sizes in island regions like the Caribbean, Oceania or the group of small island-developing countries compared to continental regions (United Nations et al., 2019). Additionally, many small island states face increasing threats of climate change driven sea-level rise, leading to forced migration (Kelman, 2010; Bellard et al., 2014). Emigration often leads to the abandonment of agricultural and highly modified regions and ecosystems. The subsequent succession in these areas often favors the establishment of alien species that are better adapted to human-modified landscapes compared to native species (Rey Benayas et al., 2007; Plieninger et al., 2014). However, many islands are tourist destinations with more people projected to arrive in the future. This emerging economic incentive might result in more people remaining or returning to islands, which would slow down expected demographic trends. Cumulative effects of demography and migration and recreation and tourism with the subsequent development of infrastructure (e.g., roads and hiking trails; Haider et al., 2018; Liedtke et al., 2020) might foster future establishment of alien species as these structures have been shown to be introduction pathways (Toral-Granda et al., 2017). Additionally, cultivation of alien species near tourist accommodations and in public green spaces further increases the probability that these species might jump the fence and establish new populations outside gardens (Cowie et al., 2008; van Kleunen et al., 2018). In several instances, charismatic alien species have as well adopted an economic value for the local community because

they attract tourists (Jarić et al., 2020). The relevance of both drivers is in agreement with our study results.

The respondents have different perceptions on the role of technology and innovation for different invasion stages in the future. While there is a tendency toward technology optimism, meaning that technological development will not result in an increase of alien species richness, about one third of respondents have the opposite opinion. This ambivalence in responses might suggest that technological development can have strongly diverging effects on biological invasions. On the one hand, environmental DNA (eDNA) is already used for early detection and rapid response to alien species introductions (Thomsen and Willerslev, 2015; Dougherty et al., 2016). Especially in aquatic systems, eDNA is a highly effective tool to detect alien species at low population densities (Dejean et al., 2012). On islands, the use of eDNA methods will very likely result in better biosecurity effectiveness due to increased early detection rates and improved IAS surveillance (Herder et al., 2014; Tingley et al., 2019). Smart applications for reporting nature observations are used in citizen science projects to detect, monitor and manage alien species (Mannino and Balistreri, 2018; Roy et al., 2018; Johnson et al., 2020) and satellite data are used via remote sensing for alien species mapping and management (Henderson and Dawson, 2009; Robin et al., 2011; Rocchini et al., 2015; Rivas-Torres et al., 2018). On the other hand, e-commerce has resulted in increased alien species introductions and has emerged as a new pathway of introductions that is difficult to manage (Lenda et al., 2014; Humair et al., 2015), which likely explains why the divergence in opinion was higher for the introduction than for the two other stages of invasion. Furthermore, upon the initial introduction of goods to major transportation hubs, secondary spread of alien species might be facilitated by more localized trade with higher transportation frequencies resulting from increased automation using, for example, block chain techniques, reduced transit times, and new consumer good distribution techniques (McKinsey Global Institute, 2019).

A similarly ambiguous assessment was provided for the effects of awareness, values and lifestyle on alien species richness



across invasion stages. Prevention of introduction and post-introduction early detection and rapid response are the most effective management options against alien species introduction (Reaser et al., 2020), which is reflected in the responses, showing that this driver has the lowest contribution toward the increase of alien species richness at the introduction stage. At later stages, building awareness might be more difficult, as many alien species that were introduced a long time ago, may have been incorporated culturally or economically into local communities and are now being perceived as “native.” For example, the prickly pear (*Opuntia ficus-indica*) was introduced to the Macaronesian islands as an economically important fodder and to obtain red and purple pigment (Prance and Nesbit, 2005). Nowadays prickly pear occurs across all islands and is even used to advertise the beauty of the islands to tourists. Another aspect related to peoples’ values toward alien species might lie in their perception of a species based on its charisma (Jarić et al., 2020) and in several instances, alien species management plans have failed due to strong opposition of the general public and activist groups (e.g., Bertolino and Genovesi, 2003; Verbrugge et al., 2013). Finally, there can be important discrepancies in the perception of alien species between archipelagos and even between islands within an

archipelago, with people in more remote islands tending to see more benefits in alien species (Meyer and Fourdrigniez, 2019). It is hence important to include all relevant stakeholders in the decision-making process for managing alien species as well as transparently communicating such actions and their relevance to the general public (Novoa et al., 2018; Shackleton et al., 2019). Especially on islands, where native biodiversity is a major economic pillar, such societal transformations with respect to awareness, values and lifestyle are crucial and feasible. However, it is likely that efforts toward societal transformation will not show their result within the near future, a delay, which probably motivated the ambivalent responses in our study.

Finally, the survey shows consensus in that knowledge generation (i.e., IAS science), dissemination (i.e., communication and outreach) and pro-active actions (i.e., IAS management) does not substantially increase future alien species richness. For a long time, islands have been at the forefront of biological research, dating back to Charles Darwin and Alfred Russel Wallace. They have provided valuable testing grounds for theory development and conservation planning (Whittaker and Fernandez-Palacios, 2007). Given their isolated nature and limited spatial extent, biosecurity measures are

TABLE 4 | Proportional odds models, analyzing how strongly an increase in alien species richness in the 21st century will affect different (A) island types, (B) island systems, and (C) island habitats.

(A) Island type			
	Odds Ratio	CI	p
Predictors			
Atoll	3.54	2.16–5.81	<0.001
Continental Island	3.43	2.12–5.57	<0.001
Oceanic Island	16.47	8.88–30.58	<0.001
Threshold coefficients:			
Low Medium	0.37	0.26–0.54	<0.001
Medium Strong	2.7	1.87–3.91	<0.001
(B) Island system			
	Odds Ratio	CI	p
Predictors			
Freshwater	5.98	3.56–10.04	<0.001
Marine	5.31	3.19–8.83	<0.001
Terrestrial	11.86	6.64–21.18	<0.001
Threshold coefficients:			
Low Medium	0.38	0.27–0.56	<0.001
Medium Strong	2.6	1.79–3.76	<0.001
(C) Island habitat			
	Odds Ratio	CI	p
Predictors			
Agricultural Land	3.28	2.01–5.37	<0.001
Mountain and Alpine	2.01	1.25–3.24	0.004
Wet/Cloud Forest	3.61	2.22–5.87	<0.001
Coastal (terrestrial)	6.71	4.02–11.20	<0.001
Dry Forest	4.3	2.64–7.01	<0.001
Marine	3.89	2.40–6.31	<0.001
Natural Grassland	3.37	2.08–5.44	<0.001
(Semi-) Deserts	0.8	0.50–1.28	0.35
Settlements	2.46	1.51–4.01	<0.001
Shrubland	3.32	2.07–5.34	<0.001
Wetlands	5.73	3.46–9.48	<0.001
Threshold coefficients:			
Low Medium	0.37	0.26–0.53	<0.001
Medium Strong	2.67	1.89–3.79	<0.001

substantially easier to implement compared to mainland regions. For example, on the Galapagos Islands, where nature-based tourism is a vital part of the local economy, IAS management is a top priority, with the highest allocated budget of 2.5 million US\$/yr in a study of 21 protected areas globally (González et al., 2008; Self et al., 2010; Shackleton et al., 2020). Similarly, New Zealand has some of the strictest biosecurity protocols regarding IAS and an ambitious governmental program (“Predator-Free NZ”) aiming to eradicate a selection of invasive predators by 2050 (Russell et al., 2015). This strong history of research communication and acknowledgment of the risk of alien species might contribute to a slowdown of future alien species richness increases on islands even though this conclusion cannot

be drawn directly from our survey (see limitations section below for a short discussion).

Effects of Increases in Alien Species Richness

Most respondents agree that effects of increases in alien species richness will occur mainly on oceanic islands, followed by atolls and continental islands. Oceanic islands show a higher degree of endemism and more disharmonic floras and faunas than the other island types (König et al., 2019; Taylor et al., 2019). This disharmony and proportion of endemism increases with island isolation (Kier et al., 2009; König et al., 2017) and at the same time isolation has been shown to increase island invasibility (Moser et al., 2018). Continental islands, on the other hand, have a more diverse set of native biota including functional guilds usually underrepresented or absent on oceanic islands and thus might be less affected by alien species introductions (Atkinson, 1989; Apanius et al., 2000). However, their proximity to the mainland generally leads to higher anthropogenic use (e.g., higher population sizes) and socio-economic exchange with the mainland (e.g., trade) and higher propagule pressure due to close proximity compared to more distant (usually oceanic) islands, facilitating species introductions (Ficetola and Padoa-Schioppa, 2009).

Respondents assumed strong impacts across all island systems (marine, freshwater and terrestrial) with the latter experiencing most dramatic impacts. While most anthropogenic activity is undoubtedly directed toward terrestrial ecosystems, all systems are tightly interconnected with strong cascading effects across all island ecosystems (Graham et al., 2018). Lower assumed impacts in marine regions might result from the fact that marine regions are less isolated from similar regions than terrestrial island regions and thus are less prone to biological invasions (results only including 17 participants out of 126 with high expertise for at least one marine taxonomic group provide a similar ranking; see **Supplementary Figure S2**). However, marine alien species introductions via the pet trade like the lionfish in the Caribbean (*Pterois volitans* and *P. miles*; Ricardo et al., 2011) have been shown to dramatically affect local environments and species communities (Ballew et al., 2016), highlighting the need to monitor and manage alien species in marine systems. It is noteworthy, that data availability on IAS and their management is particularly scarce in the marine realm (Ojaveer et al., 2015; Latombe et al., 2019a) and that therefore, our results may be influenced by this lack of knowledge and the lower taxonomic expertise of the survey participants as compared to other systems.

Lastly, island habitats that will likely experience the strongest assumed impacts in the future are coastal regions, wetlands and dry forests. Coastal habitats on islands are exposed to highest anthropogenic pressures, with major cities and transportation hubs and highest population densities found there (Russell et al., 2017; Andrew et al., 2019). Dry forest ecosystems tend to be situated close to coastal regions, especially on tropical and subtropical islands (Janzen, 1988). During the initial human colonization, many dry forest ecosystems were degraded and thus became highly vulnerable to species invasions (Janzen, 1988;

Barbé et al., 2015), a trend that will likely persist in the future. Wetlands are probably even more vulnerable to alien species introduction and establishment than other habitats, as native wetland biodiversity (especially amphibians) is highly endemic (Duellman and Trueb, 1994; Inger, 2001). The introduction of invasive species to island wetlands, such as the cane toad (*Bufo marinus*) in the Pacific and Hawaiian Islands (Eldredge, 2000; Ellison, 2009), are a serious threat to local biodiversity. For all other habitats, the respondents agree that at least medium but mainly strong impacts are likely to occur in the future. The only exceptions are agricultural land and settlements, which are probably assumed to be already highly invaded with strong impacts and consequently impacts are assumed to be low in the future, as well as mountain and alpine and (semi-) desert habitats. For the latter two, the survey did not provide a clear trend in impact severity. While both habitats provide environmental conditions that might not suit many alien species, mountains are an attractive destination for tourists who can introduce species to these habitats (Seipel et al., 2012; Alexander et al., 2016).

Limitations of the Survey

Our study aims to provide a global picture of future drivers of alien species richness on islands by targeting a large panel of diverse respondents. Necessarily, such generality imposes trade-offs with respect to the level of detail in the questions asked and the framing of the drivers, to make them applicable across regions and systems. In section 1, the drivers are defined in a broad sense (see **Table 1**) and it is thus impossible to disentangle their effects at fine scales. For example, climate change encompasses many relevant facets like temperature changes, changes in precipitation patterns or the shifts in extreme event severity or frequency or alterations of oceanic currents and ocean chemistry. All these aspects are very important at the local and regional level, however will very likely vary dramatically between different regions of the world. Follow-up studies that target specific island regions with a more differentiated and context specific set of drivers are necessary to draw such conclusions. An interesting angle would for example be to discriminate between different taxonomic groups, which was not addressed in this study. Our study nonetheless provides a valuable synthesis on which drivers to look at more specifically.

In section 1, we asked the participants to provide an assessment of the degree of their (dis)agreement that certain drivers would increase alien species richness in the future. Disagreement does not necessarily imply the opposite effect, i.e., that the driver leads to a decrease in alien species richness. This is especially relevant for a set of drivers related to communication, management and research, and technology and innovation, for which the participants disagreed with a positive effect of the drivers on alien species richness. We interpreted this result as the expression of a negative relationship between these drivers and species richness, rather than the absence of a relationship. Although this assumption cannot be directly inferred from the survey results, it is based on the similarity in expertise between the co-authors of this study and the respondents and is supported by the existing body of literature.

Expert surveys are only as representative as the sample of respondents that take part in it and the same survey among a different group of experts might produce diverging results. We acknowledge that the participants' background is skewed toward European and Northern American institutions, expertise in terrestrial systems and plants and vertebrates, a reoccurring bias in ecological research (e.g., Troudet et al., 2017; Nuñez et al., 2019). For example, the results regarding alien species richness effects on island types or systems mirror to some degree the expertise of the respondents. We thus cannot exclude any bias in the answers given but are confident of the validity of the results following our discussion and the link to existing literature. Overall, our sample size of 126 participants is substantial and the participants represent all important island regions, major taxonomic groups and relevant scientific fields. We additionally include the answer structure to the survey including only respondents with specific expertise (e.g., for taxonomic groups or realms; **Supplementary Figure S2**).

CONCLUSION

Our survey provides a comprehensive expert-based assessment of the future importance of drivers, pathways of biological invasions on islands and their effects in different contexts. Experts across different fields of expertise and with varying backgrounds have high confidence that the movements of goods and people and related activities like tourism and recreation will continue to be the major drivers of alien species introduction and subsequent spread in the future. Additionally, biotic and abiotic factors, such as land use/cover change, biodiversity loss and climate change, are acknowledged to play crucial roles in the increase of alien species richness on islands after introduction.

In the meantime, the responses from our survey suggest that experts do not expect a silver bullet that will provide a mid-term solution to alien species-related issues. Technological innovation might play out either way, supporting or restricting alien species introduction and spread. Societal processes like changes in awareness, lifestyles and values are considered to have little to no substantial effects within the next few decades. However, transformation of societal norms is crucial in the long term, and this is supported by a consensus among the respondents. The adoption of strict biosecurity measures and pro-active communication regarding the threats from alien species is believed to lead toward effective prevention and management of biological invasions.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

BL and FE designed the research. BL performed the analysis with input from GL, CC, and FE. BL led the writing of the

initial manuscript with input by GL, CC, and FE. BL designed the questionnaire with input by SDHI, HS, PW, GL, CC, and FE. All other authors contributed to writing and commented on the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fevo.2020.00280/full#supplementary-material>

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